Magnetic Systems for Four Channels of Neutrino Factory

Channels

I.Bogdanov, S.Kozub, V.Pleskach,
P.Shcherbakov, V.Sytnik,
L.Tkachenko, V.Zubko

Institute for High Energy Physics
(IHEP)

Protvino, Moscow region, 142284
Russia

Main parameters of Neutrino Factory channels:

Channel	I	II	III	IV
Channel length, m	50	40	100	100
Central field, T	1.25	1.25	1.25	3.6
Bore diameter, m	0.6	2.0	0.6	1.4
Cryostat length, m	4.8	1.8	1.1	1.0
Gap between cryostats	0.2	0.2	0.1	0.1
Number of magnets	10	20	83	90
Total stored energy, MJ	11	82	20	4300

Main parameters of magnets:

Channel	I	II	III	IV
Central field, T	1.25	1.25	1.25	3.6
Coil length, m	4.7	1.7	1.0	0.805
Bore radius, m	0.3	1.0	0.3	0.7
Total current, MA	4.69	1.93	1.08	9.64
Layer number	2	2	2	16
Total turn number	781	322	180	1608
Operating current, kA	6	6	6	6
Stored energy, MJ	1.1	4.1	0.24	48.0
Inductance, H	0.061	0.2	0.013	2.55
Radial pressure, MPa	0.61	0.61	0.61	15.2
Axial pressure, MPa	16	17	19	89
Cable dimensions, mm^2	12×2.1	10×3.2	12×2.1	7.8×6.2
Superconducting alloy	NbTi	NbTi	NbTi	Nb_3Sn
Cu/SC ratio	7:1	9:1	7:1	20:1
$I_{nominal}/I_c$	0.3	0.3	0.3	0.5
Cable length, km	1.7	2.1	0.4	8.5
Cable mass, kg	370	582	86	3600
Cryostat inner diameter, m	0.618	2.0	0.618	1.4
Cryostat outer diameter, m	0.935	2.42	0.885	2.18
Cryostat length, m	4.8	1.8	1.1	1.0
Mass of magnet, ton	3.8	8.4	1.2	8.0

Magnet design

Solenoid coil in the first three channels has two layers. NbTi superconductor in copper matrix is chosen as a current currying element.

Dimensions of superconducting cable, quantity of copper for stabilization and ratio of nominal to critical currents were determined from conditions of safety evacuation of the stored energy out of magnet during quench process:

1. The temperature of the coil hot spot is less than 300 K.
2. The voltage on magnet is not greater than 1000 V.

Operating current is equal to 6 kA, which corresponds 0.3 from the critical current at 1.25 T and 4.5 K. The ratio Cu/SC is equal to 7:1 in the first and the third channels and 9:1 in the second channel.

The superconducting coil in the fourth channel has 16 layers. Nb_3Sn has chosen as a current currying element for the channel IV with ratio Cu/SC 20:1 in superconducting cable.

The superconducting cable has kapton insulation of 0.1 mm thickness.

The coil is wound on stainless steel tube and is banded by copper shells and is cooled by liquid helium flowing through copper pipes. The pipes are soldered to the copper shells and are connected by collectors on the ends of coil.

Copper thermal shield is used to decrease heat leaks to the inner and outer surface of superconducting coils. The shield is cooled by liquid nitrogen. Surfaces of the shield are covered with 40 layers of super-insulation.

The superconducting coil and shield are hung up to a vacuum vessel in two cross-sections by two vertical suspensions and two horizontal tension members in each cross-section. This support system allows one to adjust the location of the coil both along horizontal and vertical directions. In the axial direction longitudinal members and anchor rigid on the vacuum vessel fix the cold mass.

Budget of heat leaks in the cryostat and heat load on cryogenic system

Channel	I		II		III		IV	
Temperature K	4.5	80	4.5	80	4.5	80	4.5	80
1.Cryostats:	52	650	86	1480	187	1370	300	3400
Radiations, W	30	550	52	1300	45	1120	100	2500
Supports, W	10	80	20	160	83	160	137	800
Voltage taps, W	10	20	10	20	42	90	45	100
Seals between coils, W	2		4		17		18	
2. Transfer line, W	1	20	2	20	10	200	10	200
3. 30% margin, W	17	230	32	500	63	430	90	1000
4. Total, W	70	900	120	2000	260	2000	400	4600
5.Current leads, l/h	21		41		41		21	
Mains power, kW	115	26	219	57	331	57	383	133

All channel
4,5K 80K
850 9500
124
1321

Water shield

The second and the fourth channels have RF cavities in warm bore of superconducting solenoids. The cavities emit heat load of 50 kW per 1 m length to inside surface of the vacuum vessel.

The copper shield cooled by water is used to remove this heat load. The shield is 3 mm in thickness and copper pipe of 25×1 mm is soldered on its outer surface with 100 mm pitch. In this case the temperature of shield in the middle point between neighboring turns of the pipe is just 10°C higher than water temperature.

Each superconducting solenoid has its own shield. The shields of all the magnets are connected hydraulically in parallel. The water flow rate is 1.5 kg/s, pressure loss is 0.6 MPa and heating of the flow is 16°C for each shield.

The total flow rate of water is 30 kg/s for the second channel and 135 kg/s for the fourth channel.

Quench protection

The main future of I-IV channels is essential ponderomotive forces between solenoid in axial direction: attractive forces of 60 kN in the I, III channels and 650 kN in the II channel and repulsive forces of 18000 kN in the IV channel.

These forces are equilibrated inside the magnet string except the first and last magnets. These magnets must have very strong supports that cause a large heat leaks through them.

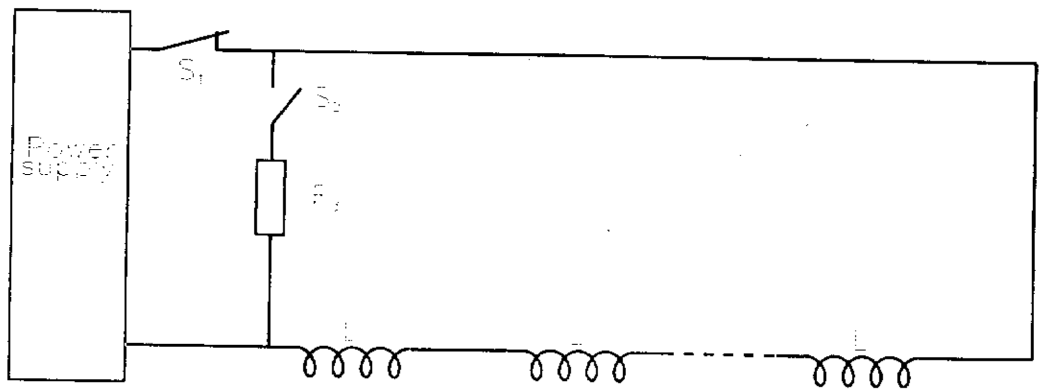
So the stored energy under the quench must be removed from all magnets simultaneously and with the identical rate in order to exclude the unbalance forces between magnets in the string.

Because of the magnets in the channel are identical, it is possible to compare the voltage drops on magnets to one another for detection of the appearance of a normal zone. The first and last magnets in the string can be equipped by the bridge type of quench detector.

Channel I

The stored energy in one solenoid placed in string of magnets is equal to 1.1 MJ. There are 10 solenoids in the channel. These magnets are connected in series and powered by one power supply. The power supply with the output power of approximately 180 kW is sufficient to rise current up to 6 kA during about 200 sec.

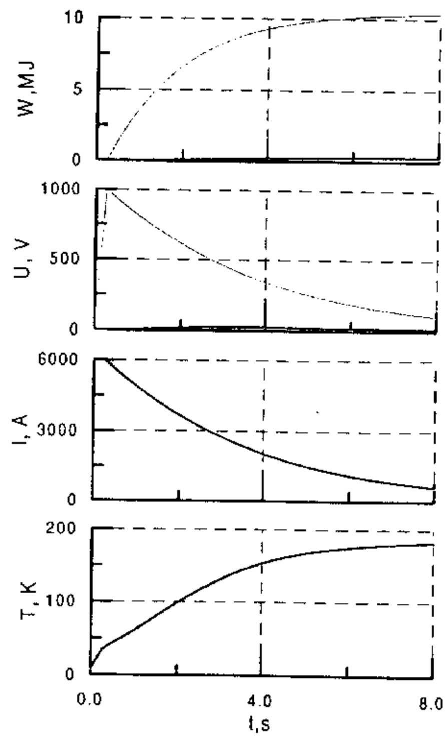
When quench detector detects the appearance of a normal zone in the coil, the dump resistor R_d is turned on by switch S_2 and power supply is switched off by S_1. At that moment the stored energy of the string starts to dissipate on the dump resistor.



Quench protection sketch of magnets in the first channel.

Simulation of quench spread through the coil was made for the case when quench was provoked on the outer boundary of inner layer of coil. The quench detector threshold was U_t = 1 V, time delay T_d = 100 ms and energy discharges on dump resistor R_d = 0.167 Ohm. The time dependences of current, dump resistor and coil voltage, energy dissipated in coil and dump resistor, and hot spot temperature are shown below.

One can see that almost 97 percent of stored energy is dissipated outside the cryostat and hot spot temperature is 180 K.

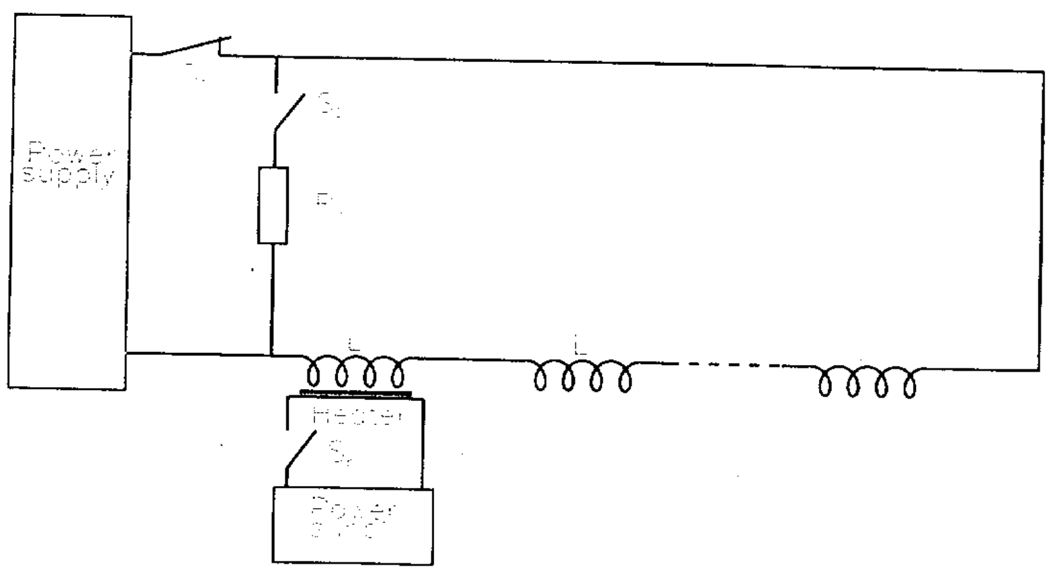


Quench process in magnets of the first channel. Thin lines correspond to dump resistor, thick lines are for superconducting coil.

Channel II

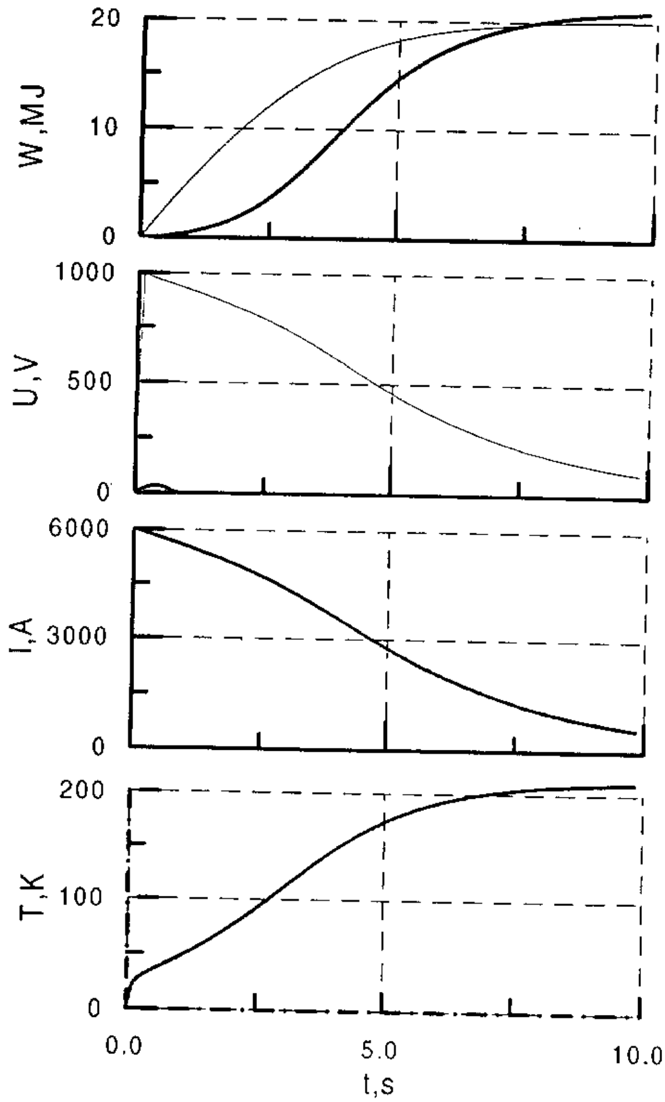
Twenty magnets of the channel store 82 MJ of energy. The magnets are connected in series and they form two independent strings with the own power supplies. The power supply with the output power of 180 kW is sufficient to rise current in string of magnets up to 6 kA during ten minutes. The scheme of one string is presented below.

There is a magnet in each string equipped by protective heater. These heaters are necessary for synchronizing of energy extraction from the strings and stimulation resistance greater than the resistance of original normal zone. Thus all strings will have the identical time constants of current dumping in order to exclude the unbalance forces in the strings.



Sketch of quench protection in one string of second and third channels.

The results of simulation of quench process initiated by heater in the string of 10 magnets are presented below. Maximum temperature in magnet with heater-initiated quench does not exceed of 210 K. The hot spot temperature in magnet with original quench is greater by 30 K and is equal to 240 K.



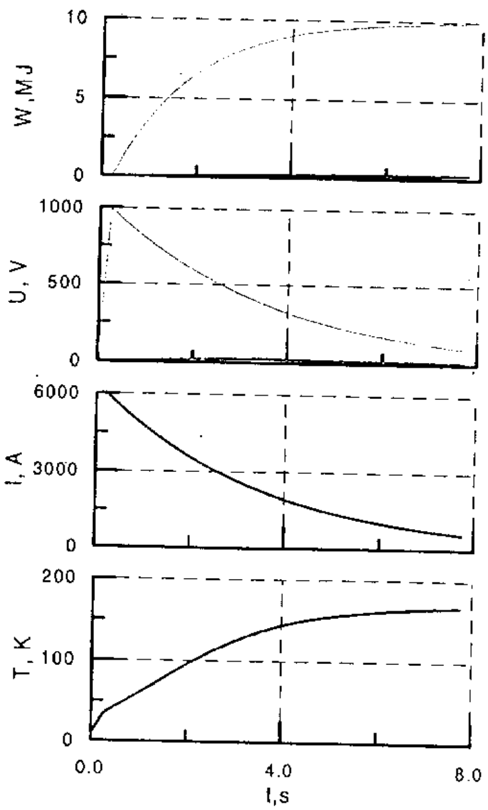
Quench process in magnets of the second channel. Thin lines correspond to dump resistor, thick lines are for superconducting coil.

Channel III

In the channel there are 83 magnets with the stored energy of 0.24 MJ each. Total energy stored in channel is 20 MJ. The magnets are connected in series and form two independent strings with 180 kW power supplies.

The quench protection concept is the same as for the second channel. Each string contains a magnet with protective heaters.

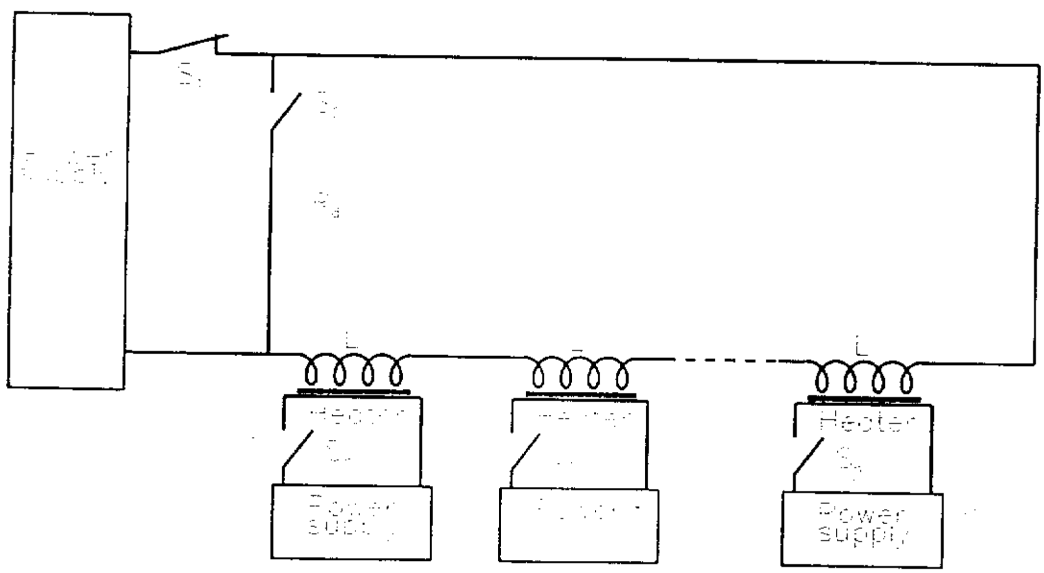
The results of simulation of quench process in the string of magnets are presented below. In this case the hot spot temperature does not exceed 200 K in magnet with original quench and 170 K in magnet with heater-initiated quench.



Quench process in magnets of the third channel. Thin lines correspond to dump resistor, thick lines are for superconducting coil.

Channel IV

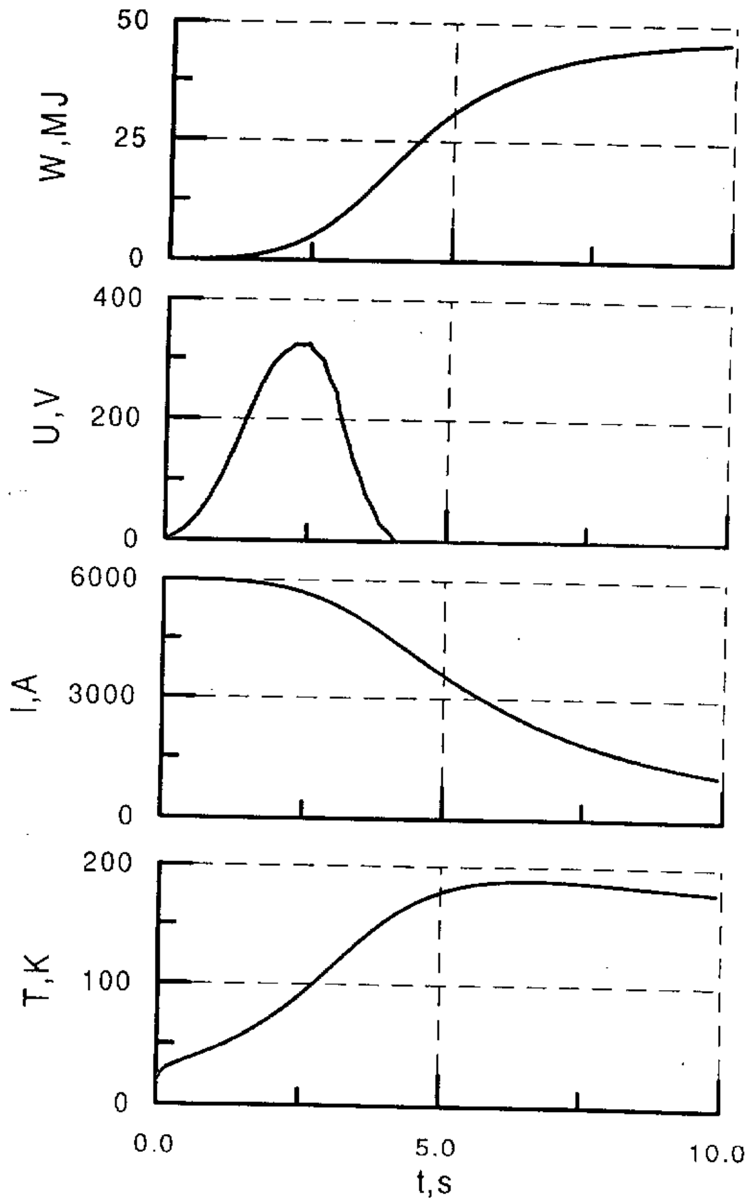
All 90 magnets of the channel are connected in series into one string. Total stored energy is about 4300 MJ. Power supply must provide of 3.0 MW that will allow one to reach the nominal current within one hour. Protective scheme is presented below. In comparison with the schemes considered above the dump resistor is absent due to inefficiency. All magnets are supplied by heaters, which are fired by switches S_h simultaneously. Stored energy of all magnets is dissipated inside the cryostats in magnet coils.



Quench protection sketch of magnets for the fourth channel.

Quench process in magnets of the fourth channel in the case when heater provoked quench is presented below. Maximum temperature of hot spot of original quench reaches about 230 K; the average temperature of coil is about 80 K.

The essential disadvantage of the IV channel protection scheme is the long time of cooling down of the magnets to 4.5 K, which can last several days.



Quench process in magnets of the fourth channel.

Main parameters of magnet power supplies:

Channel	I	II	III	IV
Operating current, kA	6	6	6	6
Voltage, V	30	30	30	500
Power, kW	180	180	180	3000
Current stability	10^{-3}	10^{-3}	10^{-3}	10^{-3}
Total inductance of magnets, H	0.61	4.0	1.1	230
Ramp rate, A/s	30	10	30	1.7
Energizing time, s	200	600	200	3600
Number of power supply	1	2	2	1

Conclusion

<u>Channel I</u> One can start to develop and design engineering drawings.

<u>Channel II</u> The magnetic attractive forces acting on the first and last magnets in the string are very large. It needs special supports in these magnets.

<u>Channel III</u> Development of the magnetic system must be close connected with development of LIA design.

<u>Channel IV</u> needs study of the questions like: the increase of field amplitude, growing of coil inner radius, the shortening of the sinusoidal field period so on.

The cost of the superconducting magnets for channel IV is by order of magnitude higher than summary cost of the magnets for channels I-III. The cost of the superconducting cable gives the basic contribution to the total cost of the fourth channel magnet. Development and production technology of the cable for this magnet is necessary to specify its design and cost.

There are many questions in development of solenoid mechanics: both radial and axial ponderomotive forces are very large as well as the interacting forces acting on the first and the last magnets in the string.

Calculations and optimization of time for magnet cooling down and warming up are needed.

Problems for R&D

1. Geometry optimization for the channel IV: optimization of different magnet parameters with the goal of increasing field amplitude, shortening field period, raising the coil inner radius.

2. Development of design and production technology of the superconducting cable for the magnet of the fourth channel.

3. Conceptual design of cryogenic system for all four channels:

   - calculations and choice of cooling circuit;

   - calculations of time for cooling down and warming up;

   - requirements to cryogenic plant.

4. Special supports of superconducting coil for the second and fourth channels.